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GRB observations by Fermi LAT revisited: new candidates found.

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ABSTRACT

We search the Fermi-LAT photon database for an extended gamma-ray emission which could be associated with any of the 581 previously detected gamma-ray bursts (GRBs) visible to the Fermi-LAT. For this purpose we compare the number of photons with energies $E > 100$ MeV and $E > 1$ GeV which arrived in the first 1500 seconds after the burst from the same region, to the expected background. We require that the expected number of false detections does not exceed 0.05 for the entire search and find the high-energy emission in 19 bursts, four of which (GRB 081009, GRB 090720B, GRB 100911 and GRB 100728A) were previously unreported. The first three are detected at energies above 100 MeV, while the last one shows a statistically significant signal only above 1 GeV.

Key words: methods: statistical, gamma-ray burst: general

1 INTRODUCTION

Gamma-ray bursts (GRBs) are one of the brightest phenomena in the Universe. Although the majority of GRBs were detected at energies ranging from hundreds of keV to several MeV, they were also observed at much higher energies up to tens of GeV (Hurley et al. 1994). The advent of the Fermi Large Area Telescope (LAT) with its unprecedented sensitivity (Atwood et al. 2009; Band et al. 2009) has greatly increased our capability to study the high-energy emission from GRBs (Omodei et al. 2009).

The high-energy (HE) emission was detected both in the prompt and afterglow phases of GRBs. However, its origin is still unclear: it could be produced in the internal/external shocks via leptonic or hadronic mechanisms, or in the process of dissipation of the Poynting flux (e.g., Meszaros & Rees (1994); Waxman (1997); Bahcall & Mészáros (2000); Zhang & Mészáros (2001); Dermer & Atoyan (2004); Fan & Piran (2008); Panaitescu (2008); Zhang & Pe'er (2009); Ghisellini et al. (2010); Kumar & Barniol Duran (2010); Razzaque et al. (2010); Zhang & Yan (2011); Mészáros & Rees (2011)). Detailed information on the high-energy γ-ray prompt and afterglow emission could shed light on the onset of GRB and its immediate interaction with surrounding interstellar medium.

GRB observations in the HE band are one of the key science topics of Fermi-LAT. The Fermi Gamma-Ray Burst Monitor (GBM) can initiate autonomous slew of the spacecraft to provide the best conditions for a dedicated GRB observation. Also, knowledge of time and position of a GRB (either provided by GBM or by other observations) makes it feasible to search for GRBs in the LAT photon database where they would manifest themselves as spatially and temporally compact clusters of photons (Band et al. 2009). There has been 20 LAT detections of GRBs as of the time of writing (Feb 2011).

Observations of several very bright bursts (GRB 080916C, GRB 090510, GRB 090902B, GRB 090926A) containing more than 100 photons with energies in excess of 100 MeV allowed one to study the spectral properties of the HE emission and even their temporal evolution (Abdo et al. 2009c,a; Ackermann et al. 2010, 2011). In all these cases the HE emission demonstrated a delay (of several seconds for long bursts, tenth of a second for the short burst GRB 090510) with respect to the prompt emission in the sub-MeV energy range. The HE emission also lasted much longer. The observations indicated a significant deviation from the so-called 'Band function' (Band et al. 1993), namely, the presence of a hard power-law component that dominates at high energies (e.g., (Abdo et al. 2009a)). Observations of the short GRB 090510 (Ackermann et al. 2010) were especially

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fruitful: first, they proved the intrinsic similarity of the HE emission between short and long bursts; second, the detection of a photon with energy over 30 GeV made it possible to evaluate the Lorentz factor of the jet $\Gamma \sim 1000$; finally, the simultaneous detection of signals in different energy ranges of GBM and LAT allowed one to put constraints on some quantum gravity theories which predict Lorentz invariance violation and energy-dependent speed of light (Abdo et al. 2009b; Ghirlanda et al. 2010).

In this letter we use the Fermi-LAT data to search for a high-energy emission related to GRBs. A similar question was addressed in a number of recent papers. In the papers by Akerlof et al. (2010, 2011) the matched filtering technique was implemented and three detections of HE emission were claimed. In the paper by Beniamini et al. (2011) the HE fluence associated with several bright GBM events was constrained.

Unlike the above studies, we looked for a HE emission that could extend over longer time spans than were examined previously and which therefore could have been missed. For this purpose we searched the LAT database for HE photons in two energy bands ($E > 100$ MeV and $E > 1$ GeV) and selected those which came from the directions of 581 previously detected GRBs within the time window of 1500 s either before or after the burst. We then estimated the statistical significance of the excess by comparing the observed number of photons with the expected background, taking into account the penalty for the total number of trials. The detection criterion was chosen in such a way that the entire search would give a single false detection with the probability of 0.05. We found 4 previously unreported GRBs showing the post-burst HE emission, and none showing the pre-burst emission.

2 DATA

The LAT detector has a sensitivity to photons with energy above 30 MeV with a wide field of view (FOV) of ~ 2.4 sr and the effective area of up to 9500 cm^2. The detector angular resolution is a function of the incident photon energy and the 'event class' which is determined by the set of reconstruction cuts (Rando 2009). It also depends on the angle between the instrument axis and the arrival direction of a photon, but for the purpose of present analysis, we use the mission-average value. An extensive review of the instrumental capabilities can be found in (Atwood et al. 2009). In this letter we use the LAT weekly all-sky data that are publicly available at Fermi mission website[1]. The analysis covers the time period of 127 weeks from August 04, 2008 to January 07, 2011, corresponding to mission elapsed time (MET) from 239557417 s to 316111862 s.

We use the 'diffuse' event class and impose an Earth relative zenith angle cut of 105°. We discard the photons from 'transient' and 'source' classes. The inclusion of these classes would decrease the signal-to-background ratio which becomes an important factor for our comparatively long time window (see Akerlof et al. (2011) for detailed discussion of event classes with respect to GRBs). We do not require the rocking angle cut of 52° in order to keep photons observed in the pointing mode, including repoint requests caused by the GRB trigger.

For the spatial selection of photons we adopt the 95% containment angle $\alpha_{95}(E, v)$ corresponding to the point spread function (PSF) for the "diffuse' class photons (Rando 2009; Abdo et al. 2009d; Burnett et al. 2009). This angle depends on both the photon energy and the conversion type v. The latter takes two discrete values: 0 and 1 for front and back converted photons, respectively.

In our analysis we used the times and coordinates of the GRBs detected by other instruments such as GBM[2] (Meegan et al. 2009), Swift[3] (Gehrels et al. 2004), INTEGRAL[4] (Winkler et al. 2003), MAXI (Matsuoka et al. 2009) and Konus-Wind (Aptekar et al. 1995). We have compiled two non-overlapping list of GRBs. The first list included 605 GRBs detected by Fermi GBM and the second 279 GRBs detected by other instruments only. Of these, 444 and 137 GRBs, respectively, were in the Fermi-LAT FOV at least for some part of 1500 s after the burst. Note that although we used time stamps from the original observations, localizations in many cases were provided by much more precise follow-up observations; these data were obtained through the Gamma-ray bursts Coordinates Network (GCN; http://gcn.gsfc.nasa.gov/).

3 METHOD

The key quantity in our analysis is the probability p that the observed HE emission from the direction of a given GRB is a fluctuation of the background. If this probability is smaller than the certain threshold, we claim the detection of the high energy emission from that burst. The significance threshold is obtained by requiring that the number of false detections does not exceed 0.05 in the entire set. Taking into account that the total number of bursts is 581 and counting two energy ranges as independent, one obtains the following condition:

$$p \ < \ 5 \times 10^{-5} \tag{1}$$

for either of the two energy regions.

The probability p for a given burst and given energy threshold E_0 is calculated as follows. Let t_b, l_b and b_b be the trigger time and galactic coordinates of a GRB. First, we determine the observed number of photons n above the energy E_0 by counting photons satisfying the following conditions:

$$\begin{gathered} E > E_0\,, \\ \alpha(l,b,l_b,b_b) < \sqrt{\alpha_{95}^2(E,v) + \alpha_{\rm GRB}^2}\,, \\ t_b \leqslant t \leqslant t_b + 1500\ {\rm s}\,, \end{gathered} \tag{2}$$

where t, l, b, E and v stand for arrival time, coordinates, energy and conversion type of a photon, $\alpha(l, b, l_b, b_b)$ is the angular separation between photon and GRB, and $\alpha_{\rm GRB}$ is the GRB pointing error. The energy threshold E_0 is either 100 MeV or 1 GeV. These conditions select photons with

[1] http://fermi.gsfc.nasa.gov/ssc/data/access/

[2] http://fermi.gsfc.nasa.gov/ssc/data/access/

[3] http://swift.gsfc.nasa.gov/docs/swift/

[4] http://www.isdc.unige.ch/integral/

GRB name	$E > 100$ MeV				$E > 1$ GeV				
	B	n	p	$\mathcal{E}$, 10^5 cm^{2}s	B	n	p	$\mathcal{E}$, 10^6 cm^{2}s	t, s
080916C	3.9	125	5.7e-138	2.16	0.065	18	6.4e-38	5.55	1500
*081009	1.9	11	4.8e-6	1.96	0.032	1	0.031	5.1	1430
081024B	0.32	5	2.3e-5	0.36	0.0044	1	4.4e-3	0.74	1500
090217A	0.82	10	1.9e-8	0.75	0.0090	1	9.0e-3	2.20	600
090323	1.2	31	2.6e-32	2.42	0.012	4	9.2e-10	3.58	1210
090328	3.5	28	1.4e-16	5.88	0.043	8	2.6e-16	8.10	1500
090510	2.8	121	7.9e-148	7.20	0.036	27	1.3e-67	9.43	1500
090626	1.1	10	3.1e-7	1.15	0.020	0	1.0	2.88	750
*090720B	4.6	16	2.4e-5	0.63	0.070	0	1.0	3.26	1500
090902B	2.6	166	8.2e-231	4.70	0.036	33	2.1e-85	6.41	1500
090926A	0.42	130	9.2e-270	0.37	0.0051	20	6.7e-65	1.49	530
091003A	3.9	25	7.6e-13	6.99	0.034	3	6.1e-6	9.16	1500
091031	2.5	13	2.2e-6	3.96	0.028	1	0.027	7.31	1500
100116A	2.1	14	5.8e-8	1.54	0.033	4	4.8e-8	3.41	820
100414A	2.9	20	6.2e-11	6.32	0.039	4	9.5e-8	8.59	1450
100724B	0.43	6	6.3e-6	0.33	0.0046	0	1	1.18	1500
*100728A	4.2	10	0.010	0.55	0.065	4	7.1e-7	8.17	1500
*100911	0.059	3	3.3e-5	0.016	0.0002	0	1	0.74	460
101014A	0.92	8	5.6e-6	0.88	0.0048	0	1	1.47	1500

Table 1. List of Fermi-LAT GRBs showing extended high-energy emission. B is the expected background, n is the observed number of photons, p is the probability that the signal is fluctuation of the background, $\mathcal{E}$ is the exposure, and t is total time duration within 1500 s interval when the angle between boresight of the telescope and the GRB position was less than 65°. Previously unreported candidates are marked with the star.

GRB name	$E > 100$ MeV				$E > 1$ GeV				
	B	n	p	$\mathcal{E}$, 10^5 cm^{2}s	B	n	p	$\mathcal{E}$, 10^6 cm^{2}s	t, s
080825C	2.3	8	2.8e-3	1.59	0.037	0	1	4.44	1330
081215A	0	0	1	0	0	0	1	0	0
100225A	2.9	4	0.33	4.06	0.042	0	1	7.22	1500
100325A	2.6	6	0.049	5.03	0.026	0	1	8.07	1500
100707A	0	0	1	0	0	0	1	0	0

Table 2. List of previously detected Fermi-LAT GRBs missed by our algorithm.

energies larger than E_0 that arrived within 1500 s after the burst from the region of interest (ROI). The latter is a circle with the energy-dependent radius determined by the two contributions: the error of the photon arrival direction and the error of the GRB position. Usually the first contribution dominates. The error of the GRB position was taken to be equal to 1° in the case of GBM bursts and 0.5° in the case of bursts detected by Swift. Errors for all other bursts were determined individually from the GCN website. The observed pre-burst photons are selected by an obvious modification of the conditions (2).

Next, we calculate the expected background B corresponding to the energy $E > E_0$. Since GRBs are exceptional events, for the background calculation we may use the photons from the same spatial region for the entire duration of the mission. Thus, the background is given by the total number of photons observed from the ROI during the whole mission, multiplied by the ratio of the exposure corresponding to 1500 s after the burst to the total exposure of ROI. The calculation which takes into account the energy dependence of ROI is presented in the Appendix A.

Finally, having calculated the observed number of photons n and the expected background B, the probability p for the GRB in question is calculated from the Poisson distribution,

$$p = \mathcal{P}(B, n),$$

where $\mathcal{P}(B, n)$ is the probability to observe n or more events at B expected. If this probability satisfies the condition (1) for at least one of the two energy regions of interest, we have a detection and include the corresponding GRB in the detection list, Table 1.

4 RESULTS AND CONCLUSIONS

Applying the method of Sect. 3 to 581 GRB we have achieved 19 detections of the post-burst HE emission, of which 4 (namely, GRB 081009, GRB 090720B, GRB 100728A and GRB 100911) were previously unreported. All detections correspond to GRBs present in the Fermi-GBM part of the GRB list. No pre-burst HE emission was found. Of the new detections, GRB 100728A demonstrated particularly bright and long HE afterglow: 4 photons with energy > 1 GeV were observed vs. 0.065 expected from the background, the chance probability being $p = 7 \cdot 10^{-7}$. Photon

arrival times relative to the burst trigger time are 711.3 s, 713.8 s, 1161.0 s and 1342.5 s. GRB 081009, GRB 090720B and GRB 100911 were observed with the rocking angle less than 52°, while during the GRB 100728A the rocking angle exceeded 52° 1220 s after the burst. The low exposure for GRB100911 is because that burst went behind the Earth shortly after the trigger and there exists a possibility of contamination from the bright Earth limb.

The total number of previously reported GRBs detected by Fermi-LAT is 20. Our algorithm failed in 5 cases; they are listed in Table 2. Two of them (GRB 081215A and GRB 100707A) resided far from the Fermi-LAT axis at approximately 90° angular distance. Their original detections were made with the use of the non-standard analysis technique (McEnery 2008; Pelassa & Pesce-Rollins 2010). Our algorithm is based on the standard event reconstruction and does not treat events outside of LAT FOV. The remaining three GRBs are seen as excesses that do not satisfy eq. (1) (in the worst case of GRB 100225 the chance probability is as large as 0.4). This discrepancy can be attributed to a wider time window used in our analysis and somewhat different energy ranges.

In our procedure we have treated the background events as a Poissonian process. This approach would fail in case of a moving gamma ray source (the Sun or the Moon) crossing the region of interest just at the moment of burst. We have explicitly checked that no such events happened for the reported candidates. We have also assumed that the background flux is stationary. This could lead to an erroneous detection if some gamma-ray sources in the region of interest flared at the moment of the GRB. This issue should be investigated separately; one can use the LAT 1-year Point Source Catalog (The Fermi-LAT Collaboration 2010) for this purpose. No known sources appear within 95% containment radius of all GeV photons attributed to GRB 100728A; the same is valid for GRB 081009. On the contrary, there are numerous sources in the neighborhoods of GRB 090720B and GRB 100911. The question of a possible influence of variability of these sources on the present analysis will be studied elsewhere (Rubtsov et al. 2011). Finally, to test for a possible influence of the magnetospheric flares[5] we calculated the gamma-ray flux during 1500 s after the burst in the ring between 15° and 20° from its location, and compared it to the expected background. No indication of magnetospheric flares coincident with the reported new detections was found.

When this paper was already submitted, analysis from the Fermi collaboration appeared confirming detection of HE emission from GRB 100728A (Abdo et al. 2011).

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APPENDIX A: BACKGROUND CALCULATION

The background expected from the region of interest during 1500 s after the burst is determined by the product of the differential flux $f(E,l,b)$ from the ROI and the detector exposure in that direction.

The number of photons coming within the time period $[t_1, t_2]$ is:

$$N = \int dE\, dl\, db\, f(E,l,b)\mathcal{E}(E,l,b,t_1,t_2),$$

where $\mathcal{E}(E,l,b,t_1,t_2)$ is the exposure of the instrument in a given direction and the time period $[t_1,t_2]$ at energy E, measured in units of $\mathrm{cm}^2\,\mathrm{s}$. This exposure is estimated using the standard Fermi-LAT tools *gtltcube* and *gtexpcube* (ScienceTools-v9r18p6-fssc-20101108).

The same number of photons can be written alternatively as

$$N = \int dE\, dl\, db\, n(E,l,b,t_1,t_2),$$

where $n(E,l,b,t_1,t_2)$ is the angular spectral density of photons detected over the period $[t_1,t_2]$. Comparing these two equations one finds:

$$n(E,l,b,t_1,t_2) = f(E,l,b)\mathcal{E}(E,l,b,t_1,t_2). \qquad \text{(A1)}$$

Therefore, knowing $n(E,l,b,t_1,t_2)$ and $\mathcal{E}(E,l,b,t_1,t_2)$ allows one to estimate the differential flux $f(E,l,b)$. Under the assumption of a time-independent flux, the best estimate is obtained using the longest possible time period $[t_{\rm start}, t_{\rm end}]$.

We represent $n(E,l,b,t_{\rm start},t_{\rm end})$ as a discrete distribution originated from all the photons observed for the whole duration of the mission $[t_{\rm start}, t_{\rm end}]$:

$$n(E,l,b,t_{\rm start},t_{\rm end}) = \sum_{i=1}^{N} \delta(E-E_i)\,\delta(l-l_i)\,\delta(b-b_i), \quad \text{(A2)}$$

where l_i, b_i, E_i are coordinates and energy of $i-$th photon. For the definition of the ROI we impose energy, spatial and time cut functions corresponding to Eq. 2:

$$\sigma_e^{E_0}(E) = \theta(E-E_0)\,,$$
$$\sigma_b(E,v,l,b) = \theta(-\alpha(l,b,l_b,b_b) + \sqrt{\alpha_{95}^2(E,v)+\alpha_{GRB}^2})\,,$$
$$\sigma_t(t) = \theta(t-t_b)\;\theta(-t+t_b+1500\text{ s})\,,$$

where $\theta(x)$ stands for Heaviside step function.

Number of background photons is estimated as a sum of

[5] We would like to thank B. Stern for pointing out this possibility.

front and back converted components each calculated with its own PSF and exposure:

$$B_{E_0} = \sum_{v=0}^{1} \int dE\, dl\, db\, f(E,l,b)\ \mathcal{E}(E,l,b,t_b,t_b+1500\text{ s}) \times \sigma_e^{E_0}(E)\ \sigma_b(E,v,l,b)\,, \tag{A3}$$

where $\mathcal{E}^v$ stands for conversion-type dependent exposure ($\mathcal{E} = \mathcal{E}^0 + \mathcal{E}^1$). We substitute f from Eq.A1 and Eq.A2 to Eq.A3:

$$B_{E_0} = \sum_{v=0}^{1}\sum_{i=1}^{N} \int dE\, dl\, db\ \frac{\delta(E-E_i)\ \delta(l-l_i)\ \delta(b-b_i)}{\mathcal{E}(E,l,b,t_{\rm start},t_{\rm end})} \times \mathcal{E}(E,l,b,t_b,t_b+1500\text{ s})\ \sigma_e^{E_0}(E)\ \sigma_b(E,v,l,b)\,.$$

Delta-functions will be integrated and E, l, b will be replaced by E_i, l_i, b_i. Sigma function will require to sum only the photons within ROI with energies larger than E_0. We finally get:

$$B_{E_0} = \sum_{v=0}^{1}\sum_{i=1}^{N} \frac{\mathcal{E}^v(E_i,l_i,b_i,t_b,t_b+1500\text{ s})}{\mathcal{E}(E_i,l_i,b_i,t_{\rm start},t_{\rm end})} \times \sigma_e^{E_0}(E_i)\ \sigma_b(E_i,v,l_i,b_i)\,,$$

where the sum formally goes through all LAT detected photons, but effectively only ones in the spatial ROI do contribute.

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